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World Urban Database and Access Portal Tools (WUDAPT), an urban weather, climate and environmental modeling infrastructure for the Anthropocene

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Capsule Summary:

WUDAPT, an International community generated urban canopy information and modeling infrastructure (Portal) to facilitate urban focused climate, weather, air quality, and energy use modeling application studies.

Abstract

WUDAPT is an international community-based initiative to acquire and disseminate climate relevant data on the physical geographies of cities for modeling and analyses purposes. The current lacuna of globally consistent information on cities is a major impediment to urban climate science towards informing and developing climate mitigation and adaptation strategies at urban scales. WUDAPT consists of a database and a portal system; its database is structured into a hierarchy representing different levels of detail and the data are acquired using innovative protocols that utilize crowdsourcing approaches, Geowiki tools, freely accessible data, and building typology archetypes. The base level of information (L0) consists of Local Climate Zones (LCZ) maps of cities; each LCZ category is associated with range of values for model relevant surface descriptors (e.g. roughness, impervious surface cover, roof area, building heights, etc.). Levels 1 (L1) and 2 (L2) will provide specific intraurban values for other relevant descriptors at greater precision, such as data morphological forms, material composition data and energy usage. This article describes the status of the WUDAPT

project and demonstrates its potential value using observations and models. As a community-based project, other researchers are encouraged to participate to help create a global urban database of value to urban climate scientists.

INTRODUCTION

The Anthropocene Epoch, the human influenced geologic time period (Crutzen and Stoermer, 2000), is linked inextricably to urbanization. Human activities in this epoch have had a demonstrable impact on climates at all scales and without proper management increased urbanization will contribute to associated extreme and unexpected weather events in cities. Currently, more than half of the planet's population resides in urban areas and by 2050, up to 75% are projected to live in cities of varying sizes (United Nations, 2014). The development of ever more powerful computer models to simulate weather and climate, air quality, hydrology and other environmental processes now allow us to evaluate the impacts of urban areas on climate processes and to assess urban vulnerabilities to natural hazards. These tools are needed to support urban management, to mitigate deleterious effects and to support resiliency strategies but require climate relevant information on urban landscapes to be effective (Masson et al., 2014)

The effect of urbanization on the environment is an outcome of its physical form (i.e. the land-cover, the materials and the geometry of buildings) and its functions (the transportation, energy usage, generation of waste products) that sustain human activities. These vary spatially and temporally and act in concert to adversely affect local climate, hydrology, biodiversity and air quality. These impact on the quality of life and sometimes enhance risks to public health; for example, the urban heat island is exacerbated during heat wave events and makes city dwellers especially exposed to heat stress. It is therefore crucial to characterize as best as possible these urban properties, so to be able to predict, via modeling (Chen et al., 2010), the hazard, exposure and vulnerabilities of urban dwellers to present and future environmental states (NRC, 2012). Sustained research on urban meteorology and climate over the past 50 years has provided insights into the layering of the urban boundary layer and its links with the underlying surface (Fig. 1a, courtesy of Tim Oke (2006)) As a result, state-of-the-science numerical models can simulate the surface energy budgets, weather, climate and air quality.

Examples include the Surface Urban Energy and Water balance Scheme (SUEWS), Weather Research & Forecasting (WRF) model, the Community Earth Systems Model (CESM) and the Community Multiscale Air Quality (CMAQ) model; each of these systems continue to evolve, providing enhanced capabilities, results and guidance at increasingly finer grid resolutions. However, these models are reliant on appropriate data that captures the spatially varying and temporally evolving characteristics of urban surfaces; Fig. 1b (courtesy of Andreas Christen) shows common urban canopy parameters (UCPs) that are needed by 'urbanized' climate models. In North America, the National Urban Database and Access Portal Tool (NUDAPT) compiled this information for parts of 40+ cities (Ching et al., 2009) but in most places the data to derive UCPs are either not available/incomplete and/or available at poor spatial/temporal resolutions. The absence of internationally consistent urban data for such purposes is recognized by global-to-urban climate science communities to be a significant impediment to scientific progress (Jackson et al., 2010; Revi et al., 2014, Baklanov et al., 2015). Overcoming this impediment is the aim of the World Urban Database and Access Portal Tool (WUDAPT) project.

In this paper we review the concepts and operational methodologies that underpin WUDAPT (Ching, 2013, Ching et al., 2016, 2017b), present some initial results and present near term plans. Our intent is to introduce the project and demonstrate its value to the climate community and, while individual experiments are introduced, the research details are referenced rather than discussed in detail.

2. WUDAPT OVERVIEW

The goals of WUDAPT are to (1) acquire and make accessible coherent and consistent descriptions and information on form and function of urban morphology relevant to climate, weather and environment studies on a worldwide bases and (2) provide a portal with tools that extract relevant urban parameters and properties for models and for model applications at appropriate scales for various climate, weather, environment, urban planning purposes. Its guiding principle is to generate “fit-for-purpose” urban data using a globally consistent methodology using available, publicly accessible input data and tools. Products created from this process are shared across multiple communities and platforms.

The data needed to apply models successfully to cities must meet several criteria. First, the modeling description of the urban surface must permit the model to resolve the temporal and spatial characteristics of the mesoscale urban boundary layer, including properties at local scales (Fig. 1a). Second, the spatial gradients of the inputs (and thus the output) fields are typically highly variable across urban landscapes; consequently any coarse model grid must represented sub-grid variations (Ching, 2013, Mouzourides et al., (2013, 2014)). Third, data requirements for urbanized models can be highly specialized; typically, they are distinguished by their need for UCP information on building height, vegetative cover, building materials, etc. (Masson, 2000, Martilli et al., 2002, DuPont et al., 2004; Otte et al., 2004; Oleson et al, 2008) (see Table 1 and Fig 1b). Fourth, for worldwide applicability, UCPs should be collected using a scheme that is consistent and reliable. Finally, given the time frame, the generation of this database should be practicable and achievable on a reasonably short time frame for greatest impact. WUDAPT adopts a pragmatic approach to meet these criteria.

The components of the urban landscape that are relevant to climate can be organized by scale into facets, elements, streets and blocks and neighborhoods (Oke et al., 2017). Facets describe flat and uniform features that are distinguished by their slope and aspect and radiative and thermal properties; elements are the combination of facets that creates 3D features like building typologies; streets and blocks represent the organization of elements to form distinct geometries and neighborhoods describe a common and repeated amalgams of facets, elements, streets and blocks over an area. To cope with this complexity, WUDAPT information is organized by level of detail (L) and data at each level is gathered using distinct methodologies and techniques.

The lowest level of detail (L0) maps cities and their surrounding natural landscape into Local Climate Zone (LCZ) types (Stewart and Oke, 2012). L1 data uses the LCZ maps to provide a sampling context for acquiring and managing information at finer scales. L2 data are complete information on all urban elements (e.g. building footprints, envelope fabrics and heights) which may exist for some, albeit coverages limited to a few cities; for example, NUDAPT data for Houston includes detailed information (dimensions and construction materials) for every building in the city center (Ching et al., 2009), and MApUCE data comprises a complete inventory of buildings in France (Masson et al., 2015).

The protocol for deriving and using L0 data is now well developed (Bechtel and et al., (2012, 2015, 2017a, 2017b); and there are currently over 80 cities globally for which data are available. The methods for acquiring, managing and using higher level data within the WUDAPT framework is being developed (see Section 4) but WUDAPT is already recognized as a framework for urban climate research to integrate more complex physical process in urban canopy models (e.g. Wouters et al., 2016).

Level 0 Data

The Stewart and Oke (2012) LCZ typology was designed primarily to describe the features that impact on the near-surface local thermal environment, specifically the roles of land-cover and anthropogenic heat on the magnitude of the observed urban heat island (e.g. Alexander and Mills, 2014). Its outstanding merit is that it is designed as a culturally neutral description of urban landscapes and critically, each of the 17 basic types (10 of which are urban or UCZ) is associated with typical value ranges for a set of key urban canopy parameters (Table 2). L0 data are derived using Landsat data, image software and the knowledge of urban experts (see Bechtel and Daneke, 2012 and Bechtel et al. 2015 & 2017a). The urban expert is critical to the process as they create the training areas (TAs), which identify the parts of the city under study that exemplify each LCZ type. This information is used to classify Landsat scenes into LCZ maps using a Random Forest (RF) classifier implemented in the SAGA software (Conrad et al. 2015)

The quality of the L0 data relies on the skill of the experts that create the TAs and considerable effort has been placed on training of the expert and independent assessment of the TA data. The current quality control scheme emphasizes the statistical reliability of a city database by randomly dividing the TAs into a set for training and a set for evaluation purposes. With each iteration, a LCZ map is generated for a given TA set and the resulting LCZs are compared with the evaluation set; overall accuracy (OA) is measured as the percent of LCZ values that are predicted correctly. Repeatedly sampling (that is, bootstrapping) from the TAs allows us to measure the robustness of the LCZ map, that is, the consistency of the LCZ map when using different sets of training areas. A WUDAPT committee that oversees the quality of the L0 data examines the final LCZ map to ensure that it provides an accurate depiction of the urban landscape. There are currently more than 80 cities that are in the WUDAPT database; the reader should refer to the website (www.wudapt.org) for updates.

Each LCZ map encodes UCP values that can be used in models, a subset of the list of parameters is shown in Table 2 from Stewart and Oke (2012) and its supplemental material); these UCPs are used in models and climate analyses. Fig. 2 shows as an example, the LCZ map for the Chicago area alongside a map of the pervious fraction that has been generated from a lookup table (Table 2); note that LCZ types are associated with ranges of UCP values. Establishing the veracity of the derived data is not straightforward, as it requires independently derived information that is comparable in scope and spatial resolution. Experiments on a few cities have shown good agreement but these tests are, to this point, limited to plan area fractions in western cities (Mills *et al.*, 2015, 2017a,b).

3) The WUDAPT Portal

The portal is designed to support climate research that requires urban information (Ching et al., 2015). Critically, it should allow users to extract relevant data at an appropriate spatial scale for modeling purposes. Currently, WUDAPT provides tools that can utilize the L0 data (Fig 3a) but other tools that require L1/L2 data are being designed; here we describe two portal tools, W2W (Fig 3b) and SCALER (Fig 3c).

The W2W tool was developed to convert L0 data into a gridded format suitable for urban schemes used in the WRF model; these include the Single Layer Urban Canopy Model (Kusaka et al., 2001, 2004) and the Building Effect Parameterization and Building Energy Model (BEP-BEM) scheme (Martilli et al., 2002, Salamanca et al., 2010). Converting the LCZ parameter information into UCPs suitable for these schemes requires some modification. For example, BEP-BEM requires information on street width, building footprints and pervious surface cover that can be estimated from the LCZ data by selecting the mid-point values of the available ranges (Table 2). It also requires information on the distribution of building heights within a grid cell, for which there is not a unique solution. The simplest option, which is in use, is to choose three heights, one close to the mid-point value (considering the constraint that it must be multiple of 5 m) with a probability of 50%, and two other heights above and below that, but within the given range and a multiple of 5 m, with a probability of 25%. The important point however is that W2W provides a standardized means for incorporating UCPs into urbanised WRF and permits greater comparability between studies (Brousse et al., 2016); some examples are shown in the next section. Current and subsequent updates of W2W documentation (Martilli et al., 2017) is provided as a link under “Resources” in www.wudapt.org

SCALER generates appropriately scaled model inputs to various modelling systems (Fig 3c). This tool uses the principle of the Multiple Resolution Analysis (MRA) to manage the multi-scale grid requirements of users (Mouzourides, et al., 2013 and 2014). Its unique feature is its ability to retain sub-grid data on the input parameters as the selected model grid scale is increased. This allows the impact of sub-grid UCP variability on resulting model outputs to be examined and enables a clearer understanding of the role and impact of such parameters on the behavior of a complex urban system. It has already been used to explore the scale dependent links between energy demand and urban weather (Neophytou et al., 2015, Mouzourides et al., 2017).

3. INITIAL ANALYSES AND SAMPLE APPLICATIONS

The innovation of the LCZ scheme explained earlier is that it provides a common platform for comparing cities in terms of urban form and, to a lesser extent, urban function (Stewart and Oke, 2012, Gal et al., 2015). Fig. 4 shows a sample of LCZ (and their corresponding urban canopy parameters) maps for a variety of cities revealing their unique and distinct spatial patterns of distribution. Thus, each urban area will have its own unique spatial distribution of urban canopy parameters and therefore, mesoscale modeling outcomes. The areal coverage for each LCZ type present is shown in Table 3 for both the region of interest (ROI) and official urban administrative area (shown in Fig. 4). Generally, relatively small proportions are occupied by compact urban neighborhoods – the exception is Shanghai but it has the smallest area within the official city boundary. Chicago and Vancouver are distinguished by the extent of the open low rise (LCZ 6) and the extent of nearby water. Low plant (LCZ D) characterizes the natural cover outside most cities but in the case of Sao Paulo it is dense trees (LCZ A).

These different LCZ geographies should give rise to different urban climate effects. To illustrate, Fig. 5 shows the LCZ maps for Sao Paulo (Brazil) and Mumbai (India) alongside MODIS derived mean annual surface temperature (MAST), which was computed from a 12 year time series of MODIS land surface temperature acquired at 22:30 local time and is a cloud free, robust and representative measure of long-term land surface temperature (Bechtel, 2015). The spatial pattern and magnitude of temperature clearly corresponds with the underlying LCZ surface cover.

In the following examples, the potential for a consistent climate-based landscape classification scheme are illustrated for the ubiquitous urban effect on temperature (i.e. the urban heat island or UHI). But of course, there are many other applications such as air quality modeling, the creation of urban climatic maps to aid climate sensitive urban design (Ren et al., 2017) and improving the representation of cities in global climate models (Feddema et al., 2015). The UHI, which includes the urban effect on surface, sub-surface and air temperatures, is one of the often-studied aspects of the urban climate. The surface UHI (UHI_{surf}) as observed from the vantage of a satellite (e.g. Fig.

5), and the near-surface (canopy level) UHI (UHI_{UCL}) are often used as measures of urban impact on building energy use and heat stress (Oke et al., 2017).

The cause of UHI_{surf} is primarily linked to the properties of construction materials (their radiative and thermal properties) and their dryness state – as consequence, urban surfaces (when viewed from above) generally tend to be warmer by day and night (Oke et al., 2017). Therefore, the magnitude of the UHI_{surf} depends on both the character of the urban surface and the nature of the surrounding non-urban landscape (vegetative cover, moisture status, season, etc.). The UHI_{surf} can be simulated by solving the surface energy balance, which accounts for the exchanges of radiation, sensible and latent heat fluxes between the surface and the overlying atmosphere. The Surface Urban Energy and Water Balance Scheme (SUEWS) model can derive these energy balance terms using commonly measured meteorological variables and information about land-cover. For a given area it requires the fractional areas occupied by paving, buildings, coniferous trees/shrubs, deciduous trees/shrubs, irrigated grass, non-irrigated grass and water. SUEWS has been evaluated across a range of urban landscapes and is ideally suited to simulate surface-air exchanges during weather dominated by clear and calm conditions that are conducive to UHI formation (Järvi et al., 2011).

Alexander et al. (2016) used SUEWS to examine the climate impacts of different urban development paths, using the example of Dublin, Ireland. Fig. 6 shows the results of a simulation experiment, comparing the average surface temperature for June for Dublin in 2026, based on projections of population growth and urban growth made in 2006. Land-cover in 2006 and 2026 was converted to LCZ types, which were then used to derive parameter values for SUEWS and simulations based on current climate. The results show a more extensive UHI_{surf} that reflects the replacement of natural surface cover by urbanisation. On the other hand, an alternative projection based on increased building density rather than expanding the urban footprint does not change the UHI_{surf} appreciably. This experiment shows the potential value of WUDAPT data in an applied planning context.

The urban canopy layer UHI (UHI_{UCL}) describes the impact of cities on the near-surface (~2 m) air temperature; typically, the near-surface air in cities is warmer than that in the surrounding natural area and is strongest at night under clear skies and calm conditions in densely built parts of the city. Although it is linked to the UHI_{surf} it has its own distinct genesis processes linked mostly to: the geometry and underlying material composition of the UCL which regulates the nighttime loss on longwave radiation (Oke et al., 2017); the thermal character of the built fabric, which stores daytime heat and anthropogenic additions of heat. Atmospheric models that simulate the UHI_{UCL} require detailed information on the character of the urban canopy. The most sophisticated models will nest the microscale details of the urban canopy layer within larger scale mesoscale processes that regulate the background climate.

Fig. 7 shows the results of a study on the Madrid UHI_{UCL} using WRF with the BEP-BEM scheme. The modeling setup consisted of 5 nested domains with Madrid located in the inner domain of 7200 km^2 (shown in the inset at the top of the figure) comprised of 240 x 270 cells at a resolution of 333 m. The W2W tool generated the UCPs corresponding to the L0 maps were used for the urban cells in the inner domain. Fig. 7 shows the simulated surface air temperature under ideal weather conditions for UHI_{UCL} formation, which shows the correspondence between the urban footprint and the magnitude of the heat island. The model output using WUDAPT data was compared with output derived using data in the European Environment Agency's Urban Atlas, http://www.eea.europa.eu/data-and-maps/explore-interactive-maps/urban-atlas-for-europe that has limited information on land cover within municipal boundaries. Observations made at a weather station network in the city provided an independent assessment of model performance. The results showed that performance of the model using L0 corresponding UCPs improved model performance by ~10% based on RMSE and Mean Bias indicators. Given the relative ease with which LCZ maps can be generated, the results show the potential to greatly improve urban modeling capacity, particularly where no other land-cover data are available (Brousse et al. 2016).

Heat waves are a leading cause of weather related fatalities globally and there is evidence that the UHI can act synergistically with expected global climate change to enhance the risk to public health in cities (Li and Bou-Zeid, 2013). In Fig. 8 the results of a study into heat stress in New Delhi, India are presented. In this study a baseline event was simulated based on a heat wave event (May 22-27th, 2015) that advected very hot and dry air into the city; during this period the maximum and minimum temperatures in New Delhi reached 46°C and 32°C, respectively. To examine the impact of urban growth on the intensity and extent of the associated heat stress, L0 data were generated for the modeling domain at two time periods (1977 and 2015) and the W2W tool was used to generate appropriate UCPs values for WRF (Niyogi et al., 2017). Simulations were performed using the synoptic forcing conditions that prevailed during the 2015 event and the NOAA Heat Index (HI) was calculated. HI represents the heat stress associated with high temperature and relative humidity as an 'apparent' temperature; in Fig. 8 the difference between the HI values for 2015 and 1977 is presented. This difference map shows that urban development has increased both the spatial extent and the magnitude of the heat stress. This example illustrates the value of improved urban land cover descriptions for extreme weather modeling predictions.

4. CURRENT STATUS and NEXT STEPS

As it stands, researchers can use open source tools and Landsat data to generate L0 data quickly, which overcomes a major obstacle to model application where there are no data currently. In addition to the projects presented above, which focused on the urban heat island there is evidence that the dynamics and chemistry simulated in urban models are sensitive to the description of the underlying city surface. Fig. 9 shows preliminary results from a study of air quality in Guangzhou, China using the single-layer urban canopy model coupled to Noah in the WRF-Chem model (Grell et al., 2005, Kusaka et al., 2001), depicted is the time-height cross-section of simulated $PM_{2.5}$ distribution in the UBL for a fair weather period (15-17 Oct. 2014) that corresponded with a pollution episode. The cross-sections show two simulations based on a generic 'urban' category (Fig. 9a) using UCP values from Zhang et al. (2010a, b) and based on WUDAPT-L0 data (Fig. 9b). The observable differences are the result of the simulated wind fields that reflect advanced urban physics parameterizations in WRF that can take advantage of the quality of urban data provided. Also, preliminary work on modeling air quality over Sao Paulo (Dirce et al., 2017) confirms that significant spatial and temporal variability in the complex 3-D flows and mixed layer height variations across the city are evident when more precise urban data (i.e. L0 data) is provided.

While WUDAPT continues to acquire L0 data for additional cities, the long-term strategy recognizes the need for a multi-dimensional approach to data gathering and processing with an emphasis on gathering additional socio-economic and surface variables. There are a number of activities underway to improve WUDAPT and its products and extend modeling application capabilities.

a. L0 data quality and UCP precision

Much of the effort in designing the protocol for L0 data has focused on ensuring the quality of the data. For example, experiments have demonstrated that using a contextual classifier that takes into account information in neighboring pixels during the LCZ mapping process can significantly improve the quality of the map (Verdonck et al., 2017). However, the quality of the training areas (TAs) remains the foundation of the protocol for generating the LCZ maps. At a minimum, L0 data should be reproducible by independent evaluators to achieve a high level of self-consistency but experience has shown that there is considerable variation among the urban experts in their creation of TAs. As part of The HUMan INfluence EXperiment (HUMINEX) initiative, Bechtel et al. (2017) investigated 94 crowd-sourced training datasets for ten different cities. The results indicate that while LCZ maps generated by TAs from one individual may be of poor quality, increasing the number of training data revisions and combining multiple training sets increases the quality of L0 data considerably.

In related work, cross-evaluations are being undertaken with comparable urban land-cover information where it is available, such as the impermeable surface cover recorded in Europe’s Urban Atlas and the built cover available in the Global Human Settlement Layer (Pesaresi et al. 2013). This work also has the potential to provide more precise UCP values for LCZ types, which is currently based on the information presented in Table 2. The objective of this endeavor is to generate guidance for assigning most probable values of UCPs by LCZs to each grid in the modeling domain.

b. Actions to acquire higher level data

Developing richer urban databases, both in terms of spatial detail and adding other relevant variables (such as building and vegetation characteristics) are a goal for the next phase of WUDAPT (Ching et al., 2017a). The information on buildings will be gathered using an approach similar to that for gathering L0 data, that is, to develop and employ an international building typology with associated physical and functional properties. Data acquisition will rely on crowdsourcing techniques such as smartphone and web-based tools and will utilize the WUDAPT community (See et al., 2015). The paradigm for this initiative is based on the MApUCE project, which employs France’s building database to extract detailed UCPs related to building dimensions, construction materials and occupation patterns (Masson et al., 2015 and 2017). Members of the Passive Low Energy Architecture (PLEA) community are helping to create the WUDAPT building typology (Ching et al., 2017b). The existing L0 data (that is, LCZ maps) will be used to provide a context for the data gathered and manage sampling across the urban landscape. The quality evaluation will require other independently derived data such as that available in some national censuses. Where possible, advanced satellite data and processing algorithms can provide high-definition data on building form (Wang and Dai, 2015); the feasibility of this has already been demonstrated by Xu et al., (2017a, b). These sources could also provide UCPs, such as building volume density, ground coverage ratio, frontal area density, open spaces and greenery coverage ratio.

c. Portal tools

WUDAPT tools are being developed to make maximum use of these data as it emerges. Priority capabilities under consideration include tools that: (a) link the database to the wide variety of urban climate models in stand-alone configurations (e.g. Grimmond et al., 2010) or as components to larger-scale models such as WRF, (b) allow weather data gathered at WMO standard stations outside cities to be transferred to urban locations (e.g. Erell and Williamson, 2006); (c) combine with other available modeling software (e.g., Vanegas 2012 a and b) and land-cover data to create future urban growth scenarios and; (d) evaluate urban risks associated with current and future climate hazards, (e.g., Hanna et al., 2015).

Further enhancements may be possible through links enabled through the Portal (www.wudapt.org). For example, given the rich datasets afforded by variety and types of remote sensed data sets beyond the traditional & basic Landsat landuse/land cover classifications. Inclusion of such information in WUDAPT would be as ancillary and auxiliary data for enhanced analyses e.g., (Comarazamy et al., 2013 and 2015, Hulley et al., 2014, Imhoff et al., 2010, and Luval et al., 2015)

5. OUTLOOK

Urban issues are rapidly moving to the forefront of the challenges posed by climate changes across a hierarchy of scales. The WUDAPT project is developing a comprehensive global archive of urban data and associated tools that will be needed to address these challenges. The WMO is exploring the use of WUDAPT as a means towards addressing its new urban services mandates expressed in Resolution 68(CG-17): Establishing WMO Cross-cutting Urban Focus in the 17th World Meteorological Congress (2015), and in development of Guide for Integrated Urban Hydrometeorological, Climate and Environmental Services (Baklanov et al., 2017). In China, WUDAPT data has already been used for urban impact analyses studies of dynamic growth in the Pearl River Delta (Ren et al. 2017) and in examining the impact of urbanization as part of China's 'One Belt, One Road' plan. WUDAPT is participating with the Group on Earth Observations (GEO) WUDAPT in the Global Human Settlement Layer Project (Pesaresi, 2013) and the Human Planet Initiative, focusing on activities associated with Global Urban Climate and Mitigation Planning actions.

WUDAPT is a successful grass roots effort, and continued community involvement is key to assuring success. Please consider engaging in and/or following the progress on [www.wudapt.org.](http://www.wudapt.org)

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LIST OF FIGURES

Figure 1. Top: Structure of the urban boundary layers (source, Oke, 2006) showing the developing of the mixed layer above the underlying surface layer in terms of a) meso, b local and c) microscale, where exchanges are modulated by urban form and functions; Bottom: Common urban canopy parameters (UCPs) that describe the character of the urban surface and are employed in models to evaluate the urban effect on wind, temperature, runoff, etc. (courtesy Andreas Christen, 2017).

Figure 2. WUDAPT level 0 data for Chicago and derived urban canopy parameters: a) the distribution and legend of Local Climate Zones derived from Landsat images using the WUDAPT protocol; b) the area fraction of pervious surface cover derived from Table 2.

Figure 3. The schematic of the WUDAPT project and its current portal tools: b) WUDAPT to WRF (W2W) tool is designed to integrate WUDAPT Table look-up UCP data for each LCZ to facilitate its use in the Weather Research Forecasting (WRF) model and c) SCALER, a tool which permits the extraction of WUDAPT type data to user specified grid resolution.

Figure 4. A comparison of WUDAPT L0 maps for selected cities: Sao Paulo, Brazil (top left), Milan, Italy (top right), Shanghai (China) (bottom left) and Vancouver, Canada. In each case the administrative boundaries of the city or municipality is shown. The LCZ legend is the same as shown in Fig. 2a.

Figure 5. WUDAPT L0 maps and mean annual surface temperature (MAST) at 22:30 local time in Kelvin (K) for Sao Paulo, Brazil (a and b) and Mumbai, India (c and d). The underlying topography shown in a) and c) is based on the Shuttle Radar Topography Mission. The LCZ legend is the same as shown in Fig. 2a.

Figure 6. The impact of urban growth on mean surface temperature for Dublin, Ireland (upper inset map). The Surface Energy and Water Scheme (SUEWS) model was run using parameters data derived from WUDAPT L0 data. Simulations were carried out for current (2006) and projected (2026) urban cover (lower inset map) using typical June weather and the map shows the difference in their surface temperatures (in Kelvin, K).

Figure 7. The simulated near surface air temperature (in Kelvin, K) over Madrid (for the fifth nested domain shown in the upper inset map) using the Weather Research Forecast (WRF) model. The urban canopy parameter values for WRF are from WUDAPT L0 data; the urbanized landscape is shown outlined in the lower inset map. The map shows surface air temperature at 0300h on 13th July 2015, during a heat wave event.

Figure 8. The simulated impact of urban development on heat stress over New Delhi, India (upper inset map). The WRF model was run using WUDAPT L0 data for 1977 and

2015, based on weather conditions for 25th May, 2015. The growth of the city over this period is shown in the lower inset map. The WRF simulation was used to calculate the NOAA Heat Index (HI), expressed as apparent temperature in Fahrenheit; the figure depicts the difference: HI_{2015}-HI_{1977}.

Figure 9. Example of air quality ($PM_{2.5}$) model sensitivity study using WRF-CHEM for (a) standard default WRF physics (for urban category as high intensity residential) vs (b) urban canopy parameterization modeling based on WUDAPT L0 data. The arrows (c) refer to the difference of vertical velocity simulations.

Table 1. Examples of urban canopy parameters (UCPs) used in urban models. The Building Energy Parameterization (BEP) scheme (Martilli et al., 2002) that is linked to the WRF in W2W specifically utilizes the Building UCPs in column 2.

Urban Canopy parameters (UCPs)		
General	**Buildings**	**Vegetation**
Mean canopy height	Mean Height	Vegetation plan area density*
Canopy plan area density*	Std Dev of heights	Vegetation top area density*
Canopy top area density*	Height histogram	Vegetation frontal area density*
Canopy frontal area density*	Wall-to Plan area ratio	
Roughness Length	Height to width ratio	Mean Orientation of Streets
Displacement height	Plan area density*	Plan area fraction surface covers
Sky View Factor	Rooftop area density*	Percent connected impervious areas
	Frontal area density*	Building material fraction

Table 2. Some of the urban canopy parameter (UCP) values associated with Local Climate Zone (LCZ) types from Stewart and Oke, 2012. Columns represent the percentage of impervious (λ_I), built (λ_b) and vegetated (λ_V) land-cover and mean height of building elements (z), sky view factor (λ_S) (see Fig 1a), albedo (α) and anthropogenic heat flux (Q_F in W m^{-2}).

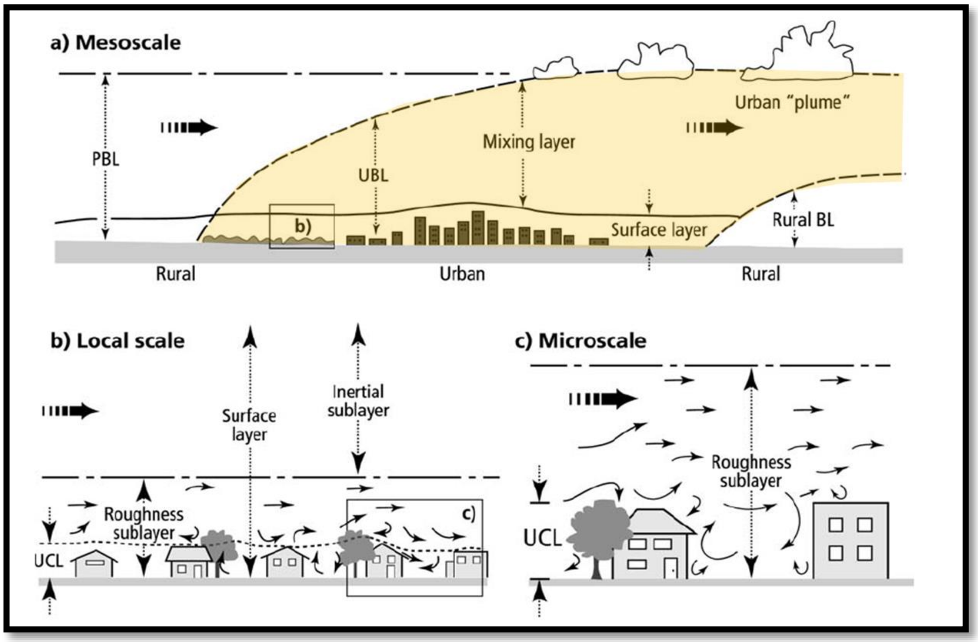
LCZ	λ_I	λ_b	λ_V	z (m)	λ_S	α	Q_F
1. Compact high-rise	40–60	40–60	<10	>25	0.2–0.4	0.10–0.20	50–300

2. Compact midrise	40–70	30–50	<20	10–25	0.3–0.6	0.10–0.20	<75
3. Compact low-rise	40–70	20–50	<30	3–10	0.2–0.6	0.10–0.20	<75
4. Open high-rise	20–40	30–40	30–40	>25	0.5–0.7	0.12–0.25	<50
5. Open midrise	20–40	30–50	20–40	10–25	0.5–0.8	0.12–0.25	<25
6. Open low-rise	20–40	20–50	30–60	3–10	0.6–0.9	0.12–0.25	<25
7. Lightweight low-rise	60–90	<20	<30	2–4	0.2–0.5	0.15–0.35	<35
8. Large low-rise	30–50	40–50	<20	3–10	>0.7	0.15–0.25	<50
9. Sparsely built	10–20	<20	60–80	3–10	>0.8	0.12–0.25	<10
10. Heavy industry	20–30	20–40	40–50	5–15	0.6–0.9	0.12–0.20	>300
101. Dense trees	<10	<10	>90	3–30	<0.4	0.10–0.20	0
102. Scattered trees	<10	<10	>90	3–15	0.5–0.8	0.15–0.25	0
103. Bush, scrub	<10	<10	>90	<2	0.7–0.9	0.15–0.30	0
104. Low plants	<10	<10	>90	<1	0.2–0.4	0.15–0.25	0
105. Bare rock or paved	<10	>90	<10	<0.25	>0.9	0.15–0.30	0
106. Bare soil or sand	<10	<10	>90	<0.25	>0.9	0.20–0.35	0
107. Water	<10	<10	>90	–	>0.9	0.02–0.10	0

Table 3. The proportion of land area occupied by each LCZ in selected cities. Each city has two values representing the areal percentage in the Region of Interest (left column) and the municipal area (as shown by the yellow boundary on Fig 4 in right column) for each LCZ. The total area is shown on the bottom row.

LCZ type	Chicago		Milan		Shanghai		Sao Paulo		Vancouver	
Compact high-rise	0.20	2.08	0.00	0.00	0.25	4.47	0.51	2.81	0.15	1.36
Compact midrise	0.10	2.39	2.11	6.32	1.35	21.56	0.10	0.31	0.00	0.06
Compact low-rise	0.19	4.00	0.10	0.25	0.77	6.23	6.39	26.04	0.47	3.93
Open high-rise	3.31	8.39	1.98	5.47	8.66	15.51	1.85	1.16	1.00	4.97
Open midrise	0.14	2.43	7.84	16.13	6.31	15.91	1.01	1.70	0.04	0.03
Open low-rise	14.54	53.92	3.57	0.38	2.44	3.20	8.03	15.57	19.97	60.18

Lightweight low-rise	0.00	0.00	0.00	0.00	4.35	2.06	1.45	3.45	0.00	0.00
Large low-rise	3.58	13.15	4.75	10.70	8.65	5.18	3.63	9.83	3.86	4.82
Sparsely built	13.01	2.78	29.69	33.47	6.16	0.05	22.12	12.54	11.30	3.44
Heavy industry	0.53	3.22	0.00	0.00	3.92	17.10	0.66	0.89	0.00	0.00
Dense trees	3.92	0.93	20.03	0.42	1.19	0.38	39.05	18.11	25.59	1.92
Scattered trees	6.85	2.28	0.47	0.51	1.63	0.31	3.07	1.62	2.02	1.73
Bush, scrub	0.00	0.00	0.00	0.00	0.00	0.00	1.51	0.50	0.00	0.00
Low plants	20.55	1.68	25.34	23.58	26.31	0.23	5.61	1.27	14.36	2.79
Bare rock or paved	0.26	0.80	1.10	2.16	0.76	1.43	0.07	0.05	0.24	0.22
Bare soil or sand	0.54	0.40	0.00	0.00	0.00	0.00	0.44	0.19	0.00	0.00
Water	32.26	1.55	3.02	0.60	27.24	6.37	4.49	3.97	21.01	14.56
Area (km^2)	15584	597	6236	1344	8887	197	9278	1410	2277	136


a) Mesoscale
Urban "plume"
PBL
Mixing layer
UBL
b)
Surface layer
Rural BL
Rural
Urban
Rural
b) Local scale
Surface layer
Inertial sublayer
Roughness sublayer
UCL
c)
c) Microscale
Roughness sublayer
UCL

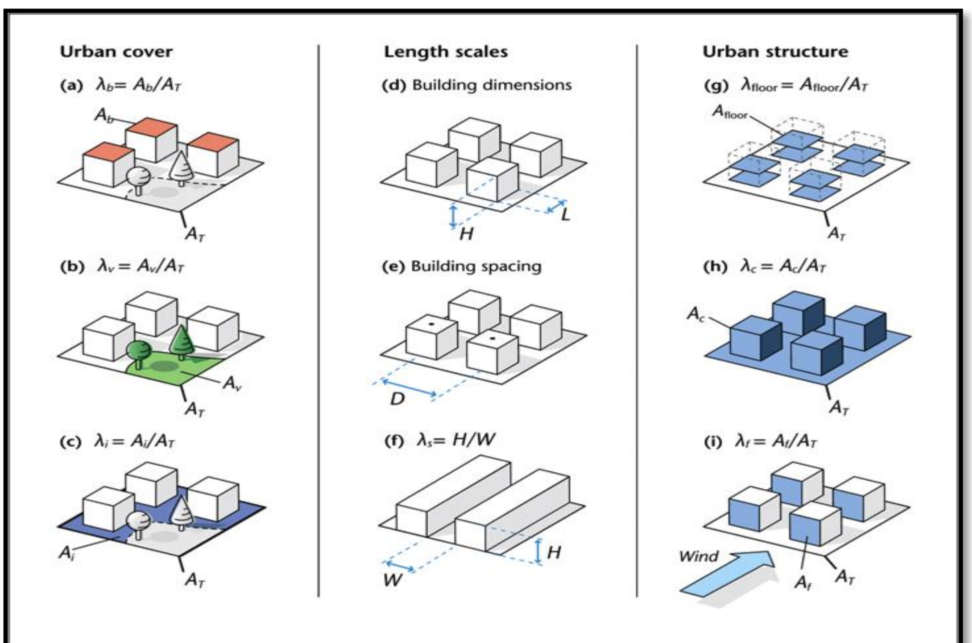

Urban cover
(a) $\lambda_b = A_b/A_T$
(b) $\lambda_v = A_v/A_T$
(c) $\lambda_i = A_i/A_T$
Length scales
(d) Building dimensions
(e) Building spacing
(f) $\lambda_s = H/W$
Urban structure
(g) $\lambda_{floor} = A_{floor}/A_T$
(h) $\lambda_c = A_c/A_T$
(i) $\lambda_f = A_f/A_T$
Wind

Fig 1. Top: Structure of the urban boundary layers (source, Oke, 2006) showing the developing of the mixed layer above the underlying surface layer in terms of a) meso, b local and c) microscale, where exchanges are modulated by urban form and functions; Bottom: Common urban canopy parameters (UCPs) that describe the character of the urban surface and are employed in models to evaluate the urban effect on wind, temperature, runoff, etc. (courtesy Andreas Christen, 2017).

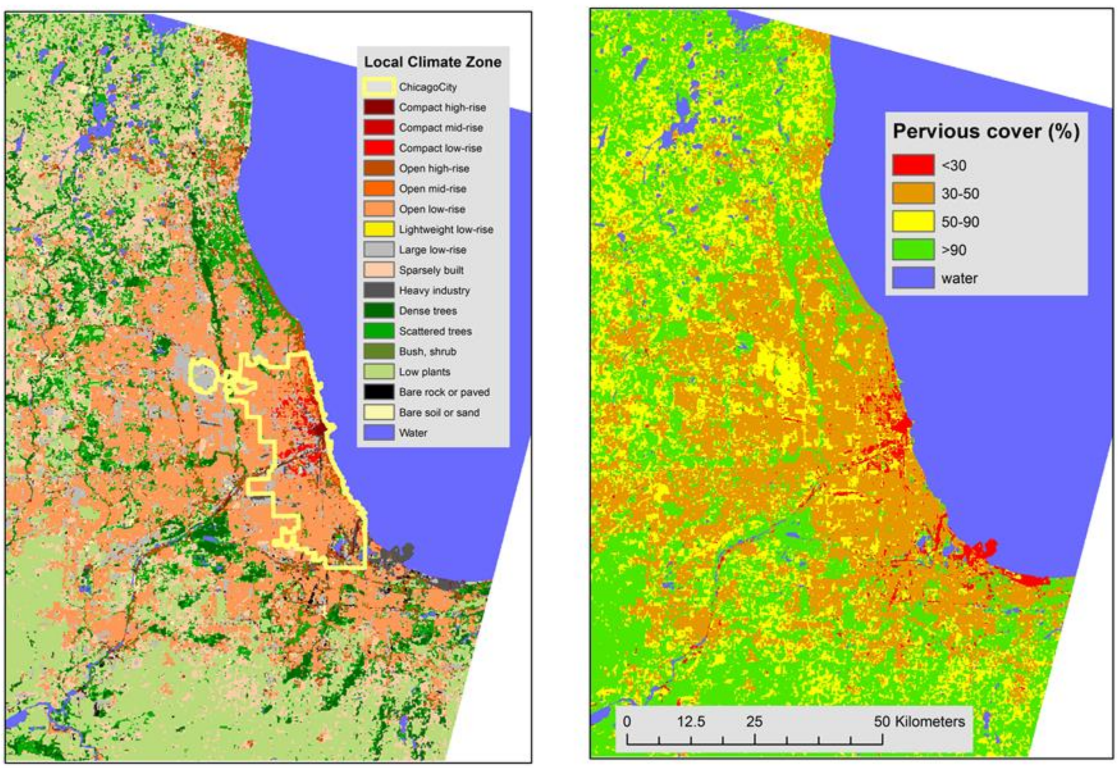


Fig 2. WUDAPT level 0 data for Chicago and derived urban canopy parameters: a) the distribution and legend of Local Climate Zones derived from Landsat images using the WUDAPT protocol; b) the area fraction of pervious surface cover derived from Table 2.

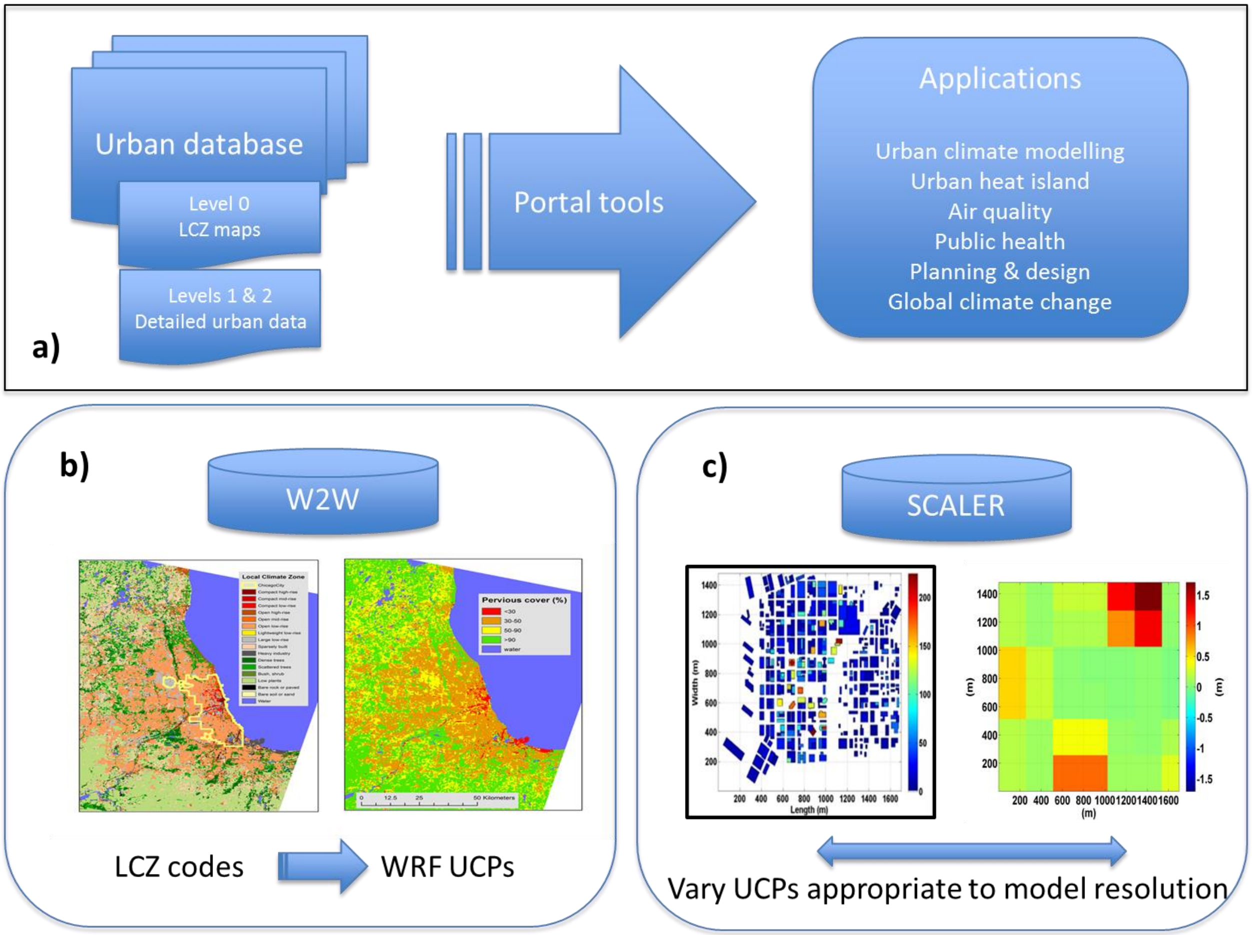


Fig 3. a) The schematic of the WUDAPT project and its current portal tools: b) WUDAPT to WRF (W2W) tool is designed to integrate WUDAPT Table look-up UCP data for each LCZ to facilitate its use in the Weather Research Forecasting (WRF) model and c) SCALER, a tool which permits the extraction of WUDAPT type data to user specified grid resolution.

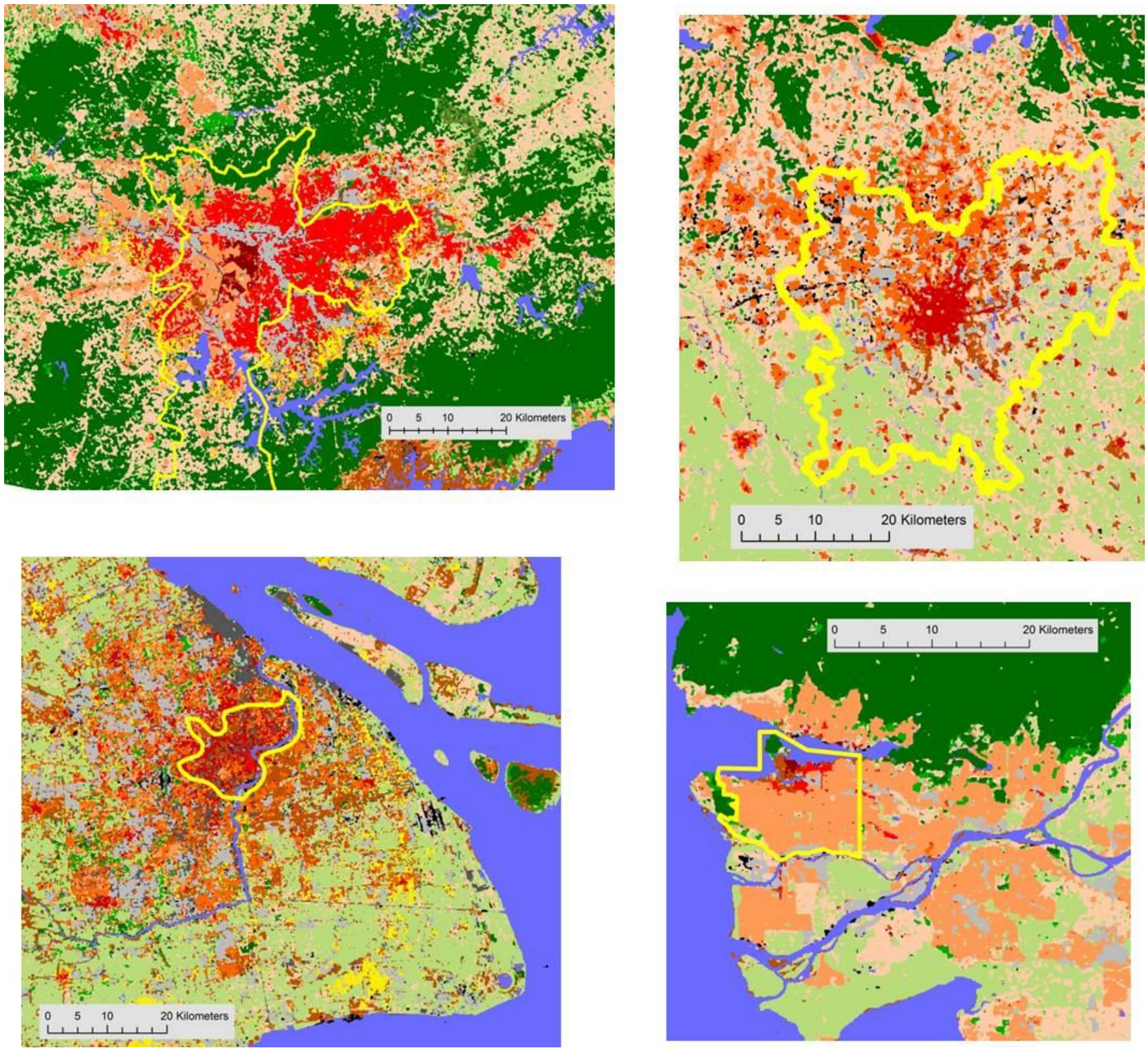


Fig 4. A comparison of WUDAPT L0 maps for selected cities: Sao Paulo, Brazil (top left), Milan, Italy (top right), Shanghai (China) (bottom left) and Vancouver, Canada. In each case the administrative boundaries of the city or municipality is shown. The LCZ legend is the same as shown in Fig. 2a.

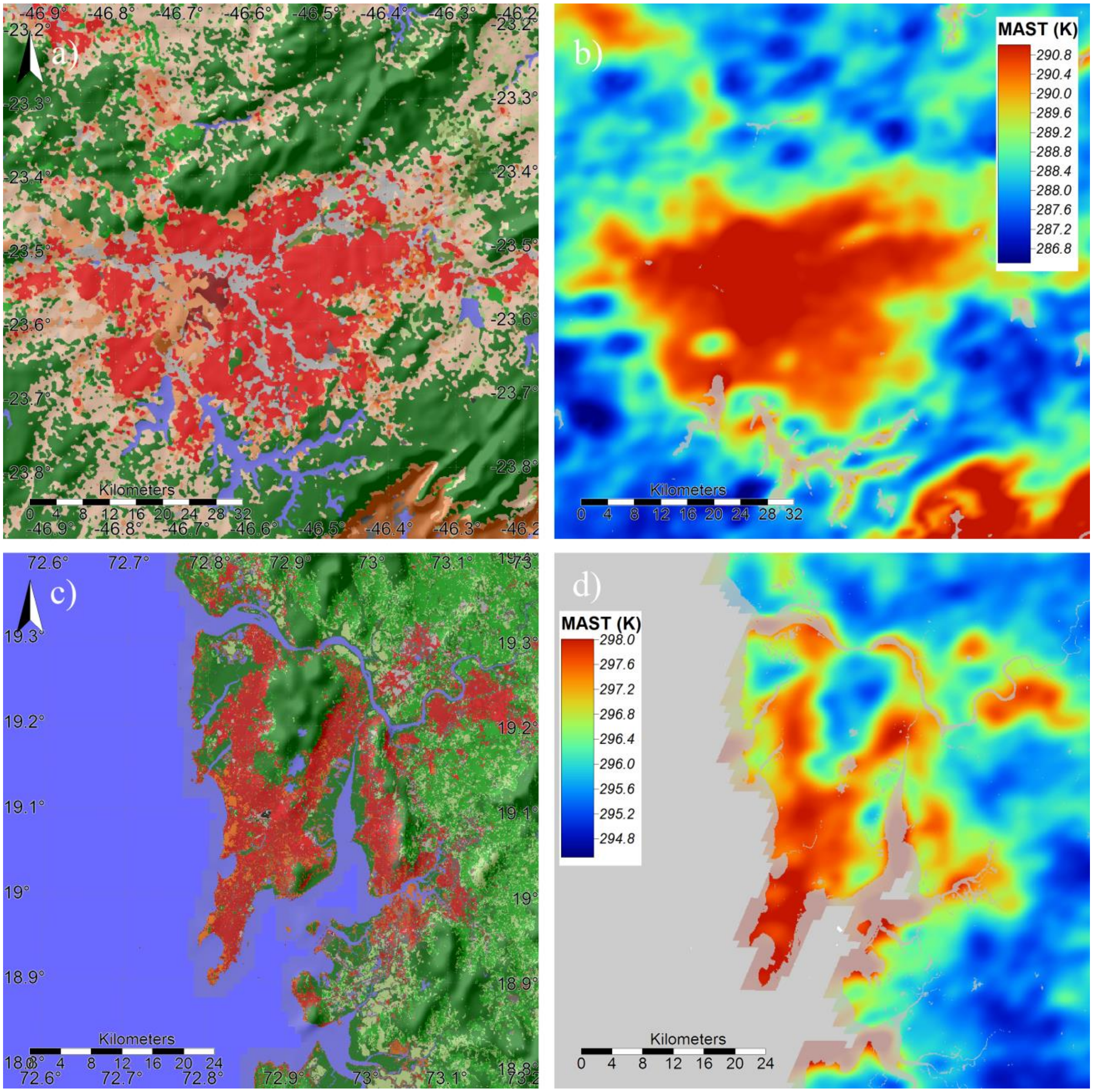


Fig 5. WUDAPT L0 maps and mean annual surface temperature (MAST) at 22:30 local time in Kelvin (K) for Sao Paulo, Brazil (a and b) and Mumbai, India (c and d). The underlying topography shown in a) and c) is based on the Shuttle Radar Topography Mission. The LCZ legend is the same as shown in Fig. 2a.

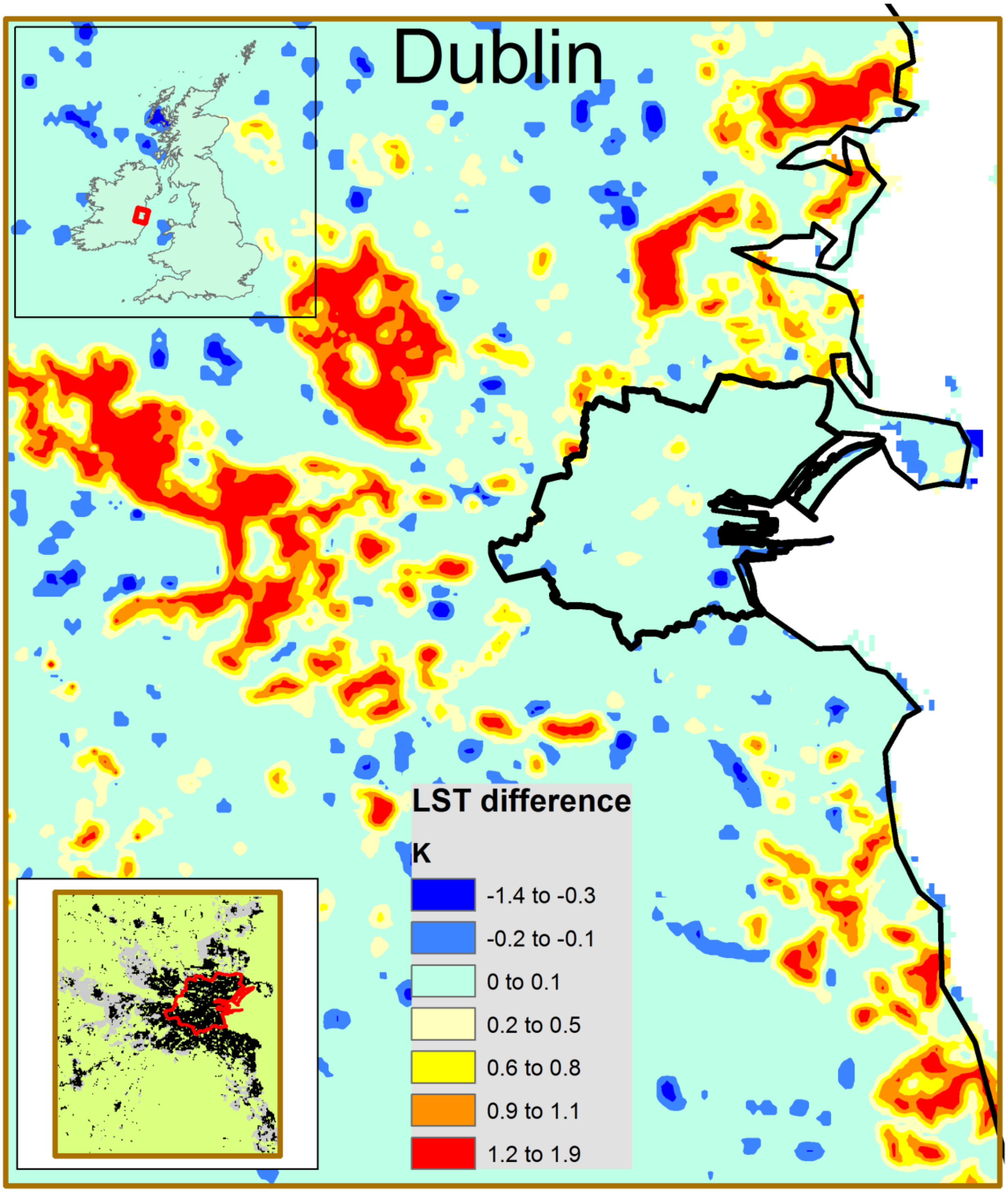


Fig 6. The impact of urban growth on mean surface temperature for Dublin, Ireland (upper inset map). The Surface Energy and Water Scheme (SUEWS) model was run using parameters data derived from WUDAPT L0 data (inset). Simulations were carried out for current (2006) and projected (2026) urban cover (lower inset map) using typical June weather and the map shows the difference in their surface temperatures (in Kelvin, K).

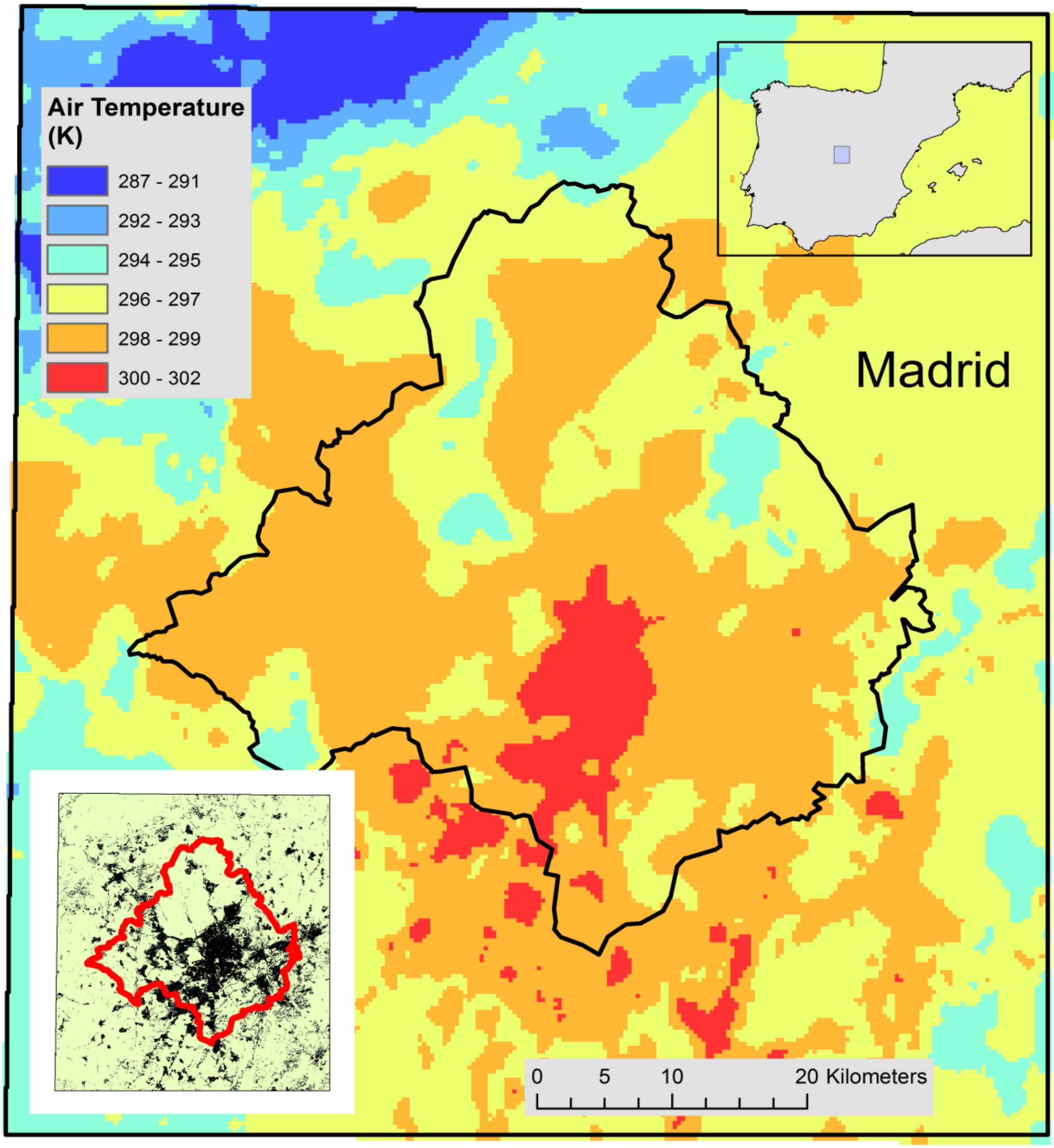


Fig 7. The simulated near surface air temperature (in Kelvin, K) over Madrid (for the fifth nested domain shown in the upper inset map) using the Weather Research Forecast (WRF) model. The urban canopy parameter values for WRF are from WUDAPT L0 data; the urbanized landscape is shown outlined in the lower inset map. The map shows surface air temperature at 0300h on 13th July 2015, during a heat wave event.

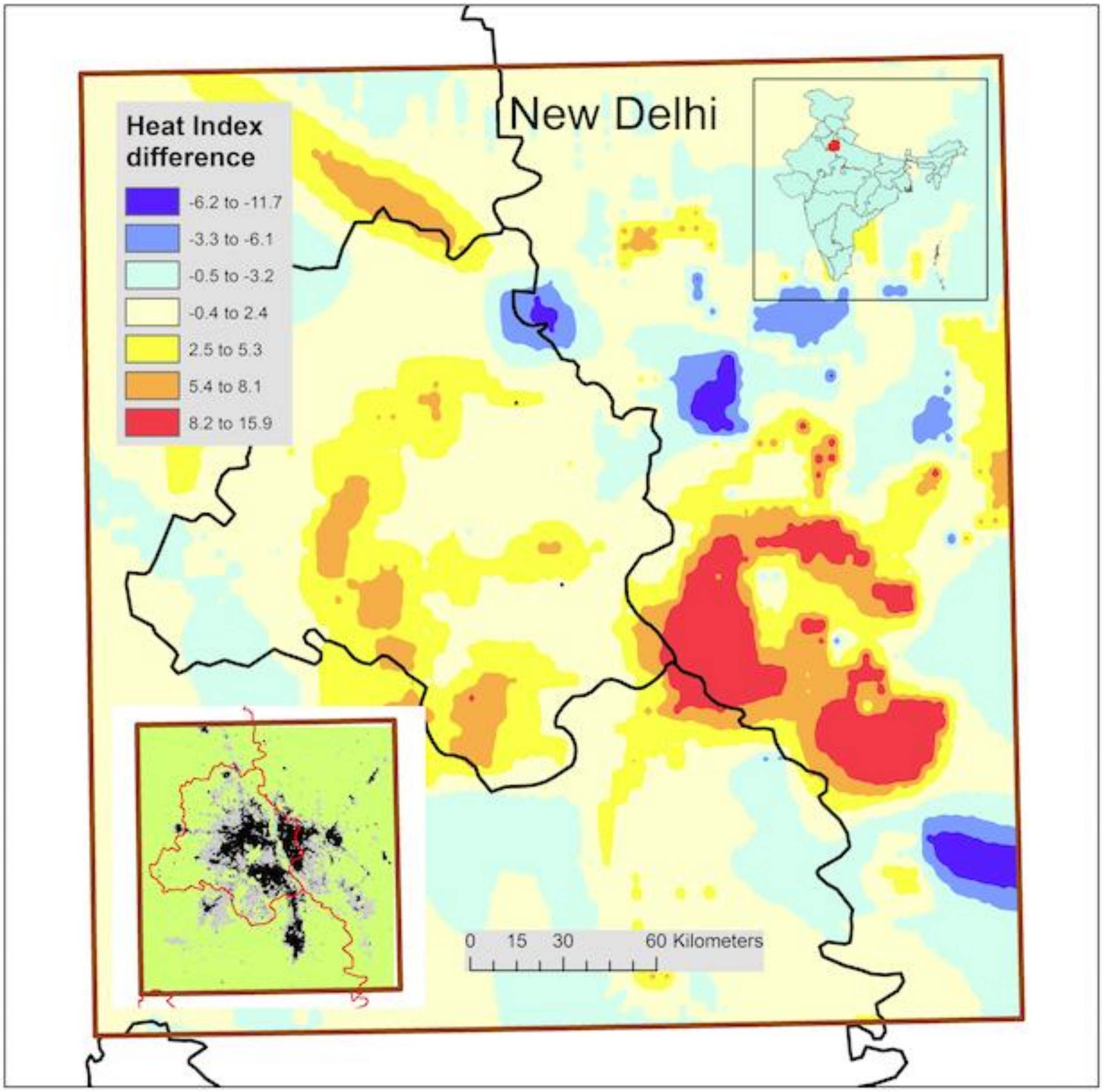


Fig 8. The simulated impact of urban development on heat stress over New Delhi, India (upper insert map). The WRF model was run using WUDAPT L0 data for 1977 and 2015, based on weather conditions for 25th May, 2015. The growth of the city over this period is shown in the lower inset map. The WRF simulation was used to calculate the NOAA Heat Index (HI), expressed as apparent temperature in Fahrenheit; the figure depicts the difference: HI_{2015}-HI_{1977}.

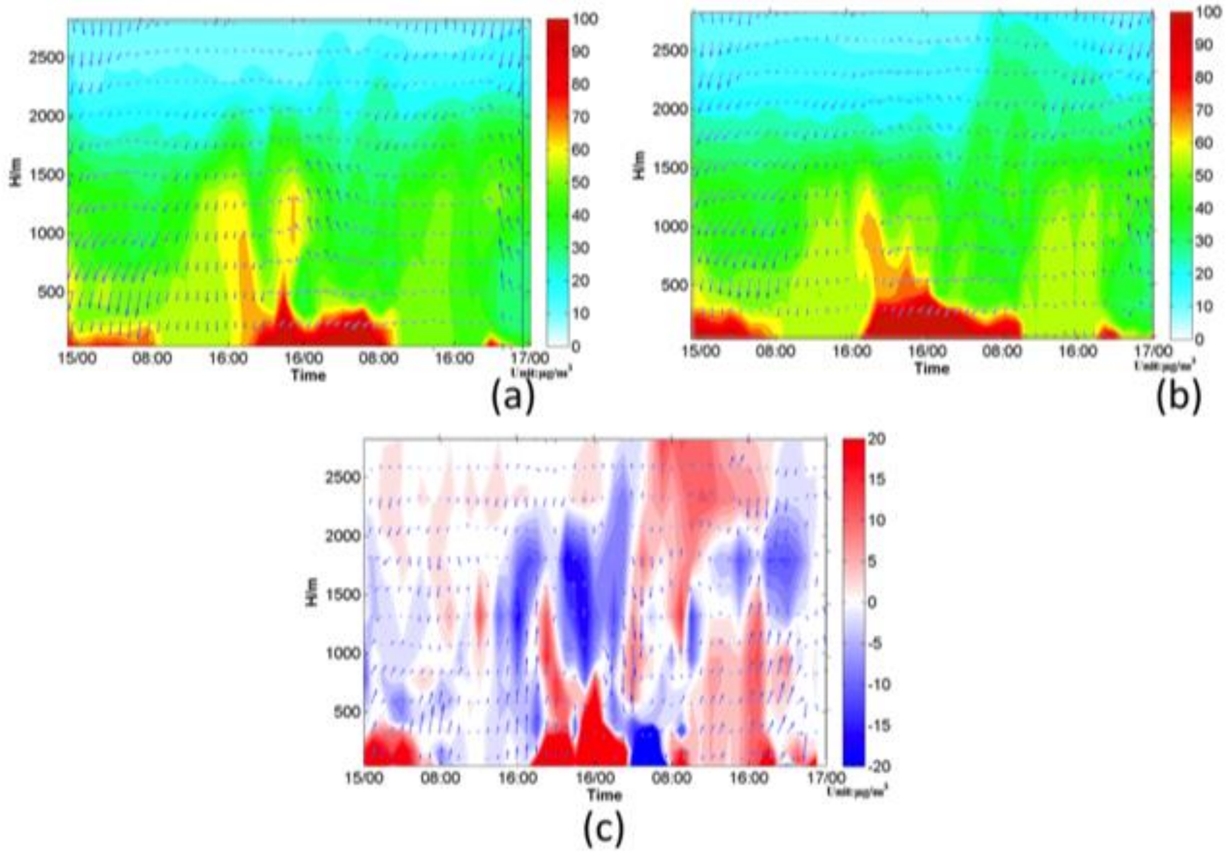


Fig 9. Example of air quality ($PM_{2.5}$) model sensitivity study using WRF-CHEM for (a) standard default WRF physics (for urban category as high intensity residential) vs (b) urban canopy parameterization modeling based on WUDAPT LCZ associated Table Lookup UCP values. The arrows (c) refer to the difference of vertical velocity simulations.